DID THE INFANT R136 AND NGC 3603 CLUSTERS UNDERGO RESIDUAL GAS EXPULSION?

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ABSTRACT

Based on kinematic data observed for very young, massive clusters that appear to be in dynamical equilibrium, it has recently been argued that such young systems set examples where the early residual gas-expulsion did not happen or had no dynamical effect. The intriguing scenario of a star cluster forming through a single starburst has thereby been challenged. Choosing the case of the R136 cluster of the Large Magellanic Cloud, the most cited one in this context, we perform direct N-body computations that mimic the early evolution of this cluster including the gas-removal phase (on a thermal timescale). Our calculations show that under plausible initial conditions as consistent from observational data, a large fraction ($> 60\%$) of a gas-expelled, expanding R136-like cluster is bound to regain dynamical equilibrium by its current age. Therefore, the recent measurements of velocity dispersion in the inner regions of R136, that indicate that the cluster is in dynamical equilibrium, are consistent with an earlier substantial gas expulsion of R136 followed by a rapid re-virialization (in ≈ 1 Myr). Additionally, we find that the less massive Galactic NGC 3603 Young Cluster (NYC), with a substantially longer re-virialization time, is likely to be found deviated from dynamical equilibrium at its present age (≈ 1 Myr). The recently obtained stellar proper motions in the central part of the NYC indeed suggest this and are consistent with the computed models. This work significantly extends previous models of the Orion Nebula Cluster which already demonstrated that the re-virialization time of young post-gas-expulsion clusters decreases with increasing pre-expulsion density.

Keywords: stars: kinematics and dynamics—open clusters and associations: individual(R136,NGC3603) —galaxies: star clusters: general—galaxies: individual(LMC)

1. INTRODUCTION

The question of how a young star cluster is formed has been debated for decades. According to the classical scenario, a cluster forms essentially through a single star-burst event. The individual proto-stellar cores within the parent or proto-cluster gas cloud approach their hydrogen-burning main-sequences (MS) to form an infant star cluster which still remains embedded within the residual gas that did not collapse to stars. This residual gas receives kinetic energy and radiation-pressure from the radiation of the massive MS and pre-main-sequence (PMS) stars until it gets unbound from the system and then escapes. This gas-removal process can be expected to be very rapid — typically faster than or similar to the dynamical crossing time of the embedded cluster (Lada & Lada 2003). The remaining gas-free cluster must expand due to the corresponding dilution of gravitational potential well. For the hypothetical case of instantaneous gas removal, the resultant cluster should get unbound if the total mass lost as gas is equal to or more than the mass remaining in the stars (*i.e.*, star formation efficiency (SFE) $\epsilon \leq 50\%$), as is true for any gravitationally self-bound system. For slower gas removal, the survivability of the gas-deprived cluster as a bound system, for $\epsilon \leq 50\%$, increases (Kroupa 2008). Two-body relaxation, which evolves the cluster towards a higher central concentration until the beginning of gas-expulsion, also enhances survival.

The above scenario, applicable to the formation of Galactic and extra-galactic young star clusters, has been first depicted by, *e.g.*, Hills (1980), Elmegreen (1983) and Mathieu (1983) either analytically or by small N

direct N-body studies (Lada et al. 1984). These milestone works have later been elaborated by Kroupa et al. (2001), Geyer & Burkert (2001) and Baumgardt & Kroupa (2007) by extensive direct N-body calculations of gas-expelling model infant clusters. Such theoretical studies, along with observations of young embedded systems (Lada 1999; Elmegreen et al. 2000), suggest a minimal star-formation efficiency of $\epsilon \approx 1/3$ for forming a bound, gas-free cluster, applicable to embedded systems initially in dynamical (or virial) equilibrium. An observational evidence of the residual gas expulsion process can be the < 2.5 Myr old Orion Nebula Cluster (ONC) whose measured velocity dispersion implies that it must be expanding (Jones & Walker 1988). While the ONC was widely considered to end-up in an unbound OB association (*e.g.*, Zinnecker et al. 1993), the detailed modelling by Kroupa et al. (2001) implies that it is rather destined to become a bound cluster very similar to the Pleiades by 100 Myr. Recent proper motion measurements of the Galactic ≈ 1 Myr old NGC 3603 Young Cluster (NYC) by Rochau et al. (2010) also suggests that its stars might be away from energy-equipartition. Notably, a demonstration of the expansion of clusters younger than a few Myr as they age is collated by Brandner (2008).

The key properties of the stellar initial mass function (IMF; Kroupa et al. 2013), in particular, its observed universality is also supported by a monolithic cluster formation scenario that involves competitive gas accretion by the most massive proto-stellar cores. For example, detailed three-dimensional, adaptive-mesh `FLASH` calculations including radiation feedback by Peters et al. (2010, 2011) well reproduce not only the general form of the uni-

versal IMF but also the relation between the total mass (in stars) of an embedded cluster and the mass of its most massive stellar member (Weidner & Kroupa 2004). Recently, Liu et al. (2012) find observational signatures of competitive accretion in the proto-cluster G10.6-0.4.

Very recently however, questions have been raised against the clustered mode of star formation, preferring instead a hierarchical or continuous star formation (*e.g.,* Bressert et al. 2010; Gutermuth et al. 2011). The latter is inferred from the stellar density distribution in young, star forming regions over a "global" scale. Notably, Pfalzner et al. (2012) showed that unless the density contrast among the individual clusters is very high any such conclusions based on surface density profiles can be highly ambiguous and is useful only when sufficiently deep and complete data are available. Furthermore, from the kinematics of several very young clusters indicating their dynamical equilibrium, in particular that of the R136 cluster in the Large Magellanic Cloud (LMC), it has been argued that they must have avoided any substantial residual gas-expulsion phase (*i.e.,* effectively have had 100% star-formation efficiency, also see Goodwin 2009 in this context); otherwise they would have been found expanding at such a young age. This has been particularly emphasized very recently by Hénault-Brunet et al. (2012). A key ingredient that might be missing in such arguments is the consideration of the re-virialization of the expanding gas-expelled cluster, *i.e.,* quick formation of a bound system after a fraction of the expanding cluster reverses back on a free-fall timescale.

The possible fate of the expanding ONC being a Pleiades-like bound system has been shown by Kroupa et al. (2001) whose models already demonstrate that the re-virialization time decreases with increasing initial cluster density (Fig. 1 of Kroupa et al. 2001). The survivability as a bound cluster after gas-removal has been studied later in detail by, *e.g.,* Baumgardt & Kroupa (2007). In this work, we find it crucial to study this issue again with particular focus on the case of R136. This becomes essential because of the current interpretations of the kinematic data of young, massive clusters such as R136, that seem to contradict the classical picture of monolithic cluster formation and the associated event of residual gas expulsion. We show that under plausible conditions, the re-virialization of an R136-like massive cluster, after the gas-removal, is prompt enough to make it be found in virial equilibrium despite of its young age. The recently obtained low (line-of-sight) velocity dispersion of single O-stars in R136 (Hénault-Brunet et al. 2012) is also found to be consistent with a re-virialized system. We also find that the much lighter NYC, on the other hand, is unlikely to be virialized at its current age of ≈ 1 Myr (Stolte et al. 2004, 2006), as indicated by Rochau et al. (2010).

2. MODEL COMPUTATIONS

2.1. *Gas removal*

A thorough modelling of gas-removal from embedded clusters is complicated by the radiation hydrodynamical processes which is extremely complex and involves uncertain physical mechanisms. For simplicity, we therefore mimic the essential dynamical effects of the gas-expulsion process by applying a diluting, spherically-symmetric ex-

ternal gravitational potential to a model cluster as in Kroupa et al. (2001). Specifically, we use the potential of the spherically-symmetric, time(t)-varying mass distribution

$$M_g(t) = \qquad M_g(0) \qquad t \leq \tau_d,$$
$$M_g(t) = M_g(0) \exp\left(-\frac{(t-\tau_d)}{\tau_g}\right) t > \tau_d. \qquad (1)$$

Here, $M_g(t)$ is the total mass in gas which is spatially distributed with the same initial Plummer density distribution (Kroupa 2008; see below) as the stars and starts depleting with timescale τ_g after a delay of τ_d. The Plummer radius of the gas distribution is kept time-invariant (Kroupa et al. 2001). Such an analytic approach is partially justified by Geyer & Burkert (2001) who perform comparison computations treating the gas with the SPH method.

The exact values of the essential parameters quantifying the gas-expulsion timescale, *viz.,* τ_g and τ_d depend on gas-physics. For simplicity, we use an average gas velocity of $v_g \approx 10$ km s^{-1} which is the typical sound-speed in an H II (ionized hydrogen) region. This gives

$$\tau_g = \frac{r_h(0)}{v_g},$$

where $r_h(0)$ is the initial half-mass radius of the stellar cluster/gas. The coupling of stellar radiation with the ionized residual proto-cluster gas over-pressures the latter substantially and can even make it radiation-pressure-dominated (RPD), for massive clusters in the initial phase of the expansion of the gas. During the RPD phase, the gas is driven out at speeds considerably exceeding the sound-speed of the ionized medium (Krumholz & Matzner 2009). Once the expanding gas becomes gas-pressure-dominated (GPD), it then continues to flow out with the sound-speed of an H II region (Hills 1980). Hence, the above τ_g, from $v_g \approx 10$ km s^{-1}, represents its *upper limit*; it can be shorter depending on the duration of the RPD state (also see Sec. 4). Notably, the initial RPD phase is crucial to launch the gas from very massive systems whose escape speed exceeds the sound-speed in H II gas (Krumholz & Matzner 2009).

As for the delay-time, we take the representative value of $\tau_d \approx 0.6$ Myr (Kroupa et al. 2001). The correct value of τ_d is again complicated by radiative gas-physics. An idea of τ_d can be obtained from the lifetimes of the ultra-compact H II (UCHII) regions which can be upto $\approx 10^5$ yr (0.1 Myr; Churchwell 2002). The very compact pre-gas-expulsion clusters (Sec. 2.2) have sizes ($r_h(0)$) only a factor of $\approx 3-4$ larger than the typical size of a UCHII region (≈ 0.1 pc). If one applies a similar Strömgren sphere expansion scenario (Churchwell 2002 and references therein) to the compact embedded cluster, the estimated delay-time, τ_d, before a sphere of radius $r_h(0)$ becomes ionized, would also be larger by a similar factor and hence close to the above representative value. Once the gas is ionized, it couples strongly with the radiation from the O/B stars and launched immediately (see above). High-velocity jet outflows from proto-stars (Patel et al. 2005) additionally facilitate the gas removal.

For super-massive clusters ($> 10^6 M_\odot$), however, a "stagnation radius" can form within the embedded cluster inside which the radiation cooling becomes suffi-

Table 1
Computed model parameters. The ONC-A/B computations are from Kroupa et al. (2001) and included for comparison. The quoted τ_{vir}s correspond to the re-virialization times of 30% of the initial cluster mass (in stars) after the delay time τ_d. The "BSE" column indicates the presence of stellar evolution.

Cluster	$M_{\mathrm{ecl}}(0)/M_\odot$	$M_g(0)/M_\odot$	$r_h(0)/\mathrm{pc}$	$Z/Z_\odot$	τ_g/Myr	$\tau_{\mathrm{cr}}(0)/\mathrm{Myr}$	τ_d/Myr	BSE	$\tau_{\mathrm{vir}}/\mathrm{Myr}$
R136	1.0×10^5	2.0×10^5	0.45	0.5	0.045	0.021	0.0, 0.6	Yes	0.9
NYC	1.3×10^4	2.6×10^4	0.34	1.0	0.034	0.038	0.0, 0.6	Yes	2.2
ONC-A	3.7×10^3	7.4×10^3	0.45	1.0	0.045	0.23	0.6	Yes	> 10
ONC-B	4.2×10^3	8.4×10^3	0.21	1.0	0.021	0.066	0.6	Yes	≈ 3

ciently efficient to possibly form second-generation stars (Wünsch et al. 2011). Also, as discussed above, the gas-outflow can initially be supersonic which generates shock-fronts. Although shocked, it is unlikely that star-formation will occur in such an RPD gas. Later, during the GPD outflow, the flow can still be supersonic in the rarer/colder outer parts of the embedded cluster where the average sound-speed might be lower than that typical for H II gas. However, it is not clear whether the cooling in the shocked outer regions would be efficient enough to form stars.

Admittedly, the above arguments do not include complications such as unusual morphologies of UCHIIs and possibly non-spherical ionization front, among others, and only provide basic estimates of the gas-removal timescales. Observationally, Galactic ≈ 1 Myr old gas-free young clusters such as the ONC and the NYC imply that the embedded phase is $\tau_d < 1$ Myr. The above widely-used gas-expulsion model does realize the essential dynamical effects on the star cluster. In particular, such simplification has practically no effect on the remaining cluster after the gas is expelled, e.g., on it's re-virialization, which is the focus of this work.

2.2. Initial configuration, stellar dynamics and evolution

The initial model embedded stellar clusters are Plummer spheres (Kroupa 2008) which the gas follows as well. This is a reasonable approximation since dense interstellar medium (ISM) filaments appear to have Plummer-like sections (Malinen et al. 2012; also see below). The $r_h(0)$ of embedded clusters are substantially smaller than the typical sizes of exposed young clusters as found in the semi-analytic calculations by Marks & Kroupa (2012). These calculations constrain the birth-density of a large number of observed clusters by their observed population of binary stars leading to a remarkable overlap with the densities of star-forming molecular clumps (Fig. 6 in Marks & Kroupa 2012). Our initial clusters thus follow the empirical relation between $r_h(0)$ and the embedded cluster mass (only the stars) $M_{\mathrm{ecl}}(0)$ by Marks & Kroupa (2012), viz.,

$$\frac{r_h(0)}{\mathrm{pc}} = 0.10^{+0.07}_{-0.04} \times \left(\frac{M_{\mathrm{ecl}}(0)}{M_\odot}\right)^{0.13 \pm 0.04}, \quad (2)$$

which is a rather weak dependence. This independently obtained result is in excellent agreement with the observed results from *Herschel* (André et al. 2011; Fig. 6.3). The star formation efficiency is taken to be $\epsilon = 1/3$, i.e., $M_g(0) = 2M_{\mathrm{ecl}}(0)$ (see Sec. 4 for a discussion). Notably, André et al. (2011) and Malinen et al. (2012)

refer to the shape and the compactness of ISM *filament* sections. The star forming spherical/spheroidal proto-clusters form within the ISM filaments and at their intersections (Schneider et al. 2012); a part of the filament that collapses under self-gravity to form an embedded cluster would become spherical/spheroidal. Recent *Herschel* observations of ridges in molecular clouds and of the associated filaments support this (Hennemann et al. 2012; Schneider et al. 2010; Hill et al. 2011). The compact sizes (≈ 0.1 pc) of these ISM filaments (André et al. 2011) then dictate the high compactness of the initial embedded systems. There is, of course, the competing viewpoints whether all the stars form within one cloud (the standard scenario) or the final cluster can be formed hierarchically (see Sec. 1). Currently, the possibility of forming massive stars within the filaments but outside any cluster has also been suggested (e.g., Bressert et al. 2012). So far our computations in this paper are concerned, we adopt the standard scenario and investigate whether the observed kinematics of the young clusters like R136 and NYC (to start with) can be reasonably explained within such a context. In that case, our chosen initial conditions well reflect the sizes and the shapes of the observed filaments.

The IMFs of the clusters are chosen to be canonical (Kroupa 2001) with the most massive star following the $m_{\max} - M_{\mathrm{ecl}}(0)$ relation of Weidner & Kroupa (2004). To that end an "optimized sampling" algorithm (Kroupa et al. 2013) is used instead of randomly sampling the IMF. All the computed models are fully mass-segregated using the method of Baumgardt et al. (2008), as observed in young clusters (Littlefair et al. 2003; Chen et al. 2007; Portegies Zwart et al. 2010). For computational ease, we take all the members of the initial cluster to be single stars. Since the O-stars in young clusters are typically found in binaries (Sana & Evans 2011; Sana et al. 2012), our initial stellar population, admittedly, does not completely represent that of a young cluster. However, binarity is *unlikely* to substantially influence the expansion of a cluster during gas-expulsion and re-collapse and virialization thereafter, which is the focus of this work. Although the initial segregated state is detected for several Galactic young clusters, it is yet to be confirmed for young clusters in general (see Portegies Zwart et al. 2010 for a discussion). Therefore, for comparison purposes, we compute identical models *without* any initial mass-segregation. We find that mass-segregation does not influence the conclusions (Sec. 3.1).

The dynamical evolution of the model clusters are computed using the state-of-the-art NBODY6 code (Aarseth 2003). In addition to integrating the particle orbits using the highly accurate fourth-order Hermite scheme and

dealing with the diverging gravitational forces in close encounters through regularizations, NBODY6 also employs the well-tested analytical stellar and binary evolution recipes of Hurley et al. (2000, 2002), *viz.*, the SSE and the BSE schemes. NBODY6 also includes the time-variable Plummer gas potential as described above.

The initial masses of the computed model embedded clusters are chosen to be $M_{\rm ecl}(0) \approx 10^5 M_\odot$ which is an upper mass limit of R136 (Crowther et al. 2010). Their Plummer radii are chosen from Eqn. (2). We also consider an embedded cluster of $M_{\rm ecl}(0) = 1.3 \times 10^4 M_\odot$ to mimic the gas-removal from a Galactic NYC-like cluster (Stolte et al. 2004, 2006; Rochau et al. 2010). The metallicities of the former models are taken to be $Z = 0.5 Z_\odot$, as appropriate for the LMC, and that for the NYC model it is $Z = Z_\odot$. Our computed models are summarized in Table 1, where those in Kroupa et al. (2001) are also added for comparison. For both of our computed models, the τ_gs are similar to the initial crossing times $\tau_{\rm cr}(0)$; $\tau_g \approx 2$ and 1 time(s) $\tau_{\rm cr}(0)$ for the R136 and the NYC model respectively. Since $\tau_g < \tau_{\rm cr}(0)$ for the Kroupa et al. (2001) models, our gas-expulsions are less "prompt" owing to higher initial concentrations. The MCLUSTER program (Küpper et al. 2011) is used to set the initial configurations. As it is difficult to model the weak tidal field of the LMC, the clusters are evolved in absence of any galactic potential.

3. RESULTS

3.1. *Gas-expulsion from an R136-like cluster*

Fig. 1 shows the evolution of the Lagrange radii, R_f, in our computed R136 model clusters (Table 1) with $\tau_d = 0.6$ (top panel) and 0 (bottom) Myr. The $\tau_d = 0$ case is computed as a test case only to compare with that of the more realistic delay $\tau_d = 0.6$ Myr. From the beginning of the gas-expulsion, the cluster expands rapidly with timescale τ_g. At least 60% of the cluster, by mass, then collapses back to a steady size, *i.e.*, regains virialization in $\tau_{\rm vir} \approx 1$ Myr (beyond τ_d). The inner regions virialize even earlier. Given that the bulk of the R136 cluster is ≈ 3 Myr old (Andersen et al. 2009), it ought to be currently in dynamical equilibrium as a whole *even if it has undergone a substantial gas-expulsion phase in the past.* We discuss this further in Sec. 4. The gas-free cluster is expanded by a factor of ≈ 3 in terms of its half-mass radius, r_h, after reverting to dynamical equilibrium. Notably, *the re-virialization happened in spite of the wind mass-loss from the massive stars* that was operative during these computations. Comparison of the two panels in Fig. 1 makes it apparent that a finite τ_d (with τ_g unchanged) keeps the form of the cluster's expansion and re-virialization identical — it merely applies a time-translation to the overall evolution.

Fig. 2 shows the R_f-evolution for identical R136 models but without initial mass-segregation. It demonstrates that the cluster evolutions are throughout identical to the previous cases with primordial mass segregation, in particular during the expanding phase and the re-collapse to virialization. In other words, primordial mass-segregation has no effect on the re-virialization of a cluster.

Very recently, Hénault-Brunet et al. (2012) measured radial/line-of-sight velocities (RV) of *single* O-stars
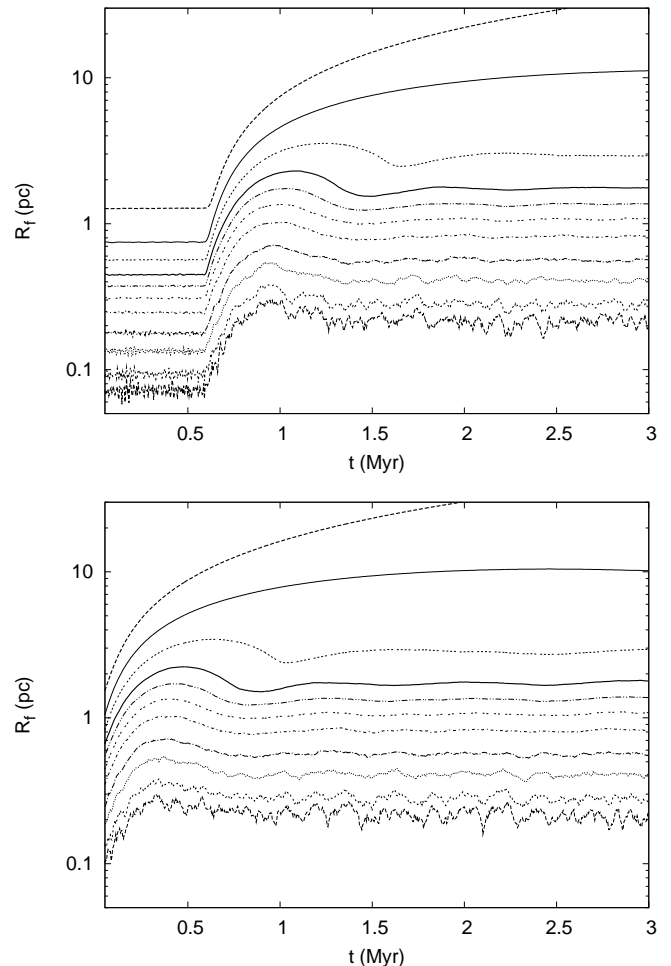
Figure 1. The evolution of the Lagrange radii, R_f, for stellar cluster mass fractions f (escaping stars inclusive) for the computed R136 models with $\tau_d = 0.6$ Myr (top) and $\tau_d = 0$ (bottom). In each panel, the curves, from bottom to top, correspond to $f = 0.01$, 0.02, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.625, 0.7 and 0.9 respectively. The thick solid line is therefore the half mass radius of the cluster.

within $1\,{\rm pc} \lesssim R \lesssim 5\,{\rm pc}$ projected distance from R136's center[1] with data obtained from the "VLT-FLAMES Tarantula Survey" (VFTS; Evans et al. 2011). They conclude that the RV dispersion, V_r, of the single O-stars within this region is $4\,{\rm km\,s^{-1}} \lesssim V_r \lesssim 5\,{\rm km\,s^{-1}}$, conforming with R136 being in virial equilibrium.

Fig. 3 shows the evolution of V_r corresponding to the R136 computations in Fig. 1 for $1\,{\rm pc} < R < 5\,{\rm pc}$ projection from the density center and stellar masses $M > 16 M_\odot$, *i.e.*, those of the O-stars. It demonstrates that, after re-virialization, the O-stars indeed have V_r remarkably similar to that measured by Hénault-Brunet et al. (2012). The initial large fluctuations in V_r in the upper panel of Fig. 3 ($\tau_d = 0.6$ Myr) is due to the initial mass-segregated condition which results in only a few O-stars within $1\,{\rm pc} < R < 5\,{\rm pc}$ initially. The measured RV data is therefore consistent with R136 being through a gas-expulsion phase and then in a re-virialized state now,

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[1] Strictly, the distances were measured from the most massive cluster member star R136a1. The exact location of the R136's true density center being unknown, we consider this star be expectedly very close to the cluster's density center.
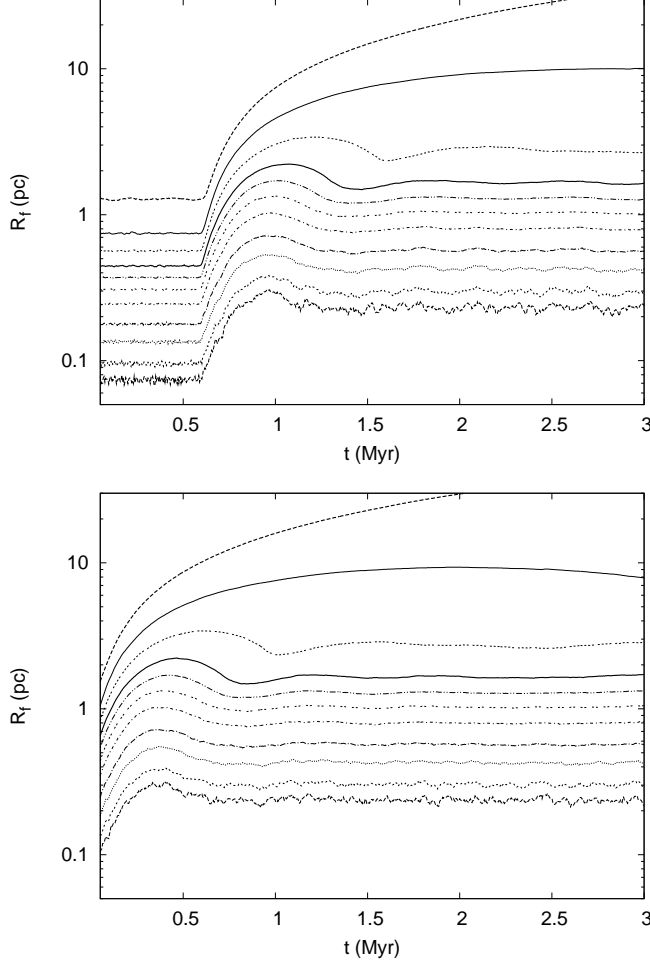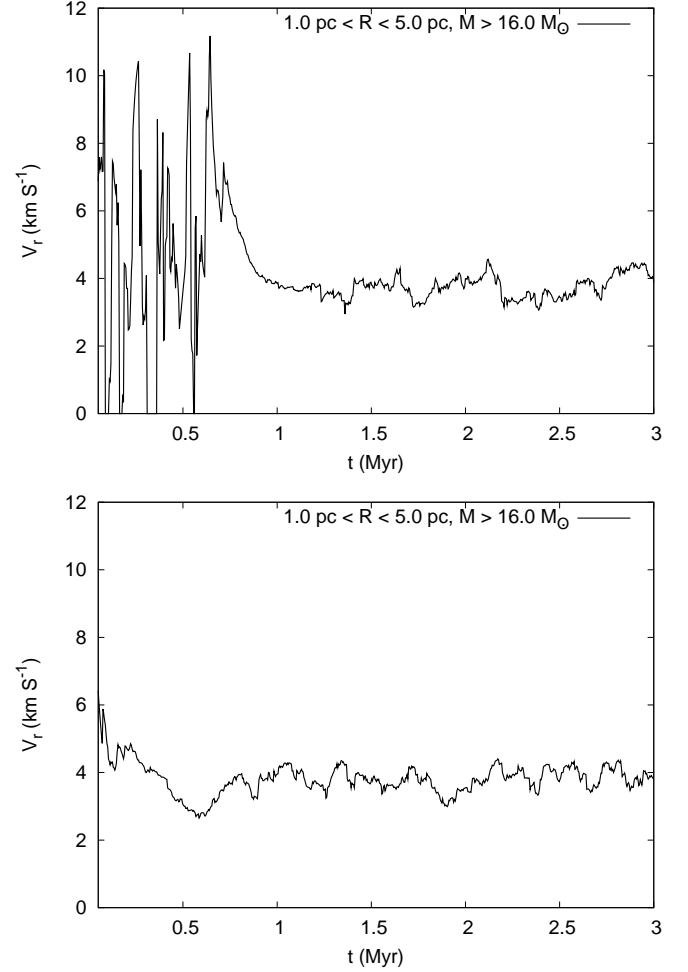
Figure 2. The evolution of Lagrange radii, R_f, for computed models without any initial mass-segregation but otherwise identical to the R136 models in Fig. 1. The legends are the same as in Fig. 1.
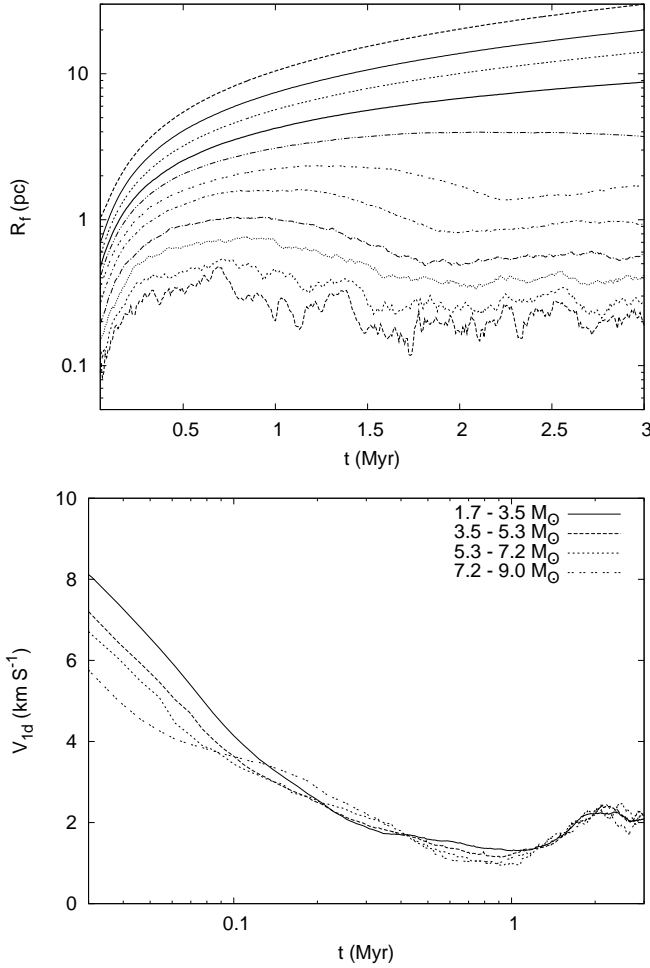
Figure 3. The evolution of the radial velocity (RV) dispersion, V_r, of the O-stars ($M > 16 M_\odot$), within the projected distances 1 pc < R < 5 pc from the cluster center, for the computed R136 models. The top and the bottom panels correspond to the computations with $\tau_d = 0.6$ and 0 Myr respectively.

unlike claimed by Hénault-Brunet et al. (2012).

3.2. *The case of the NGC 3603 Young Cluster*

Fig. 4 (top) shows the Lagrangian radii of our computed NYC cluster (Table 1). The mass of NYC (Stolte et al. 2004, 2006; Rochau et al. 2010) is substantially smaller than that of R136, implying a longer free-fall and hence re-virialization time. The model is computed with $\tau_d = 0$, which is rather unrealistic, to see the effect of the earliest possible gas removal. Even then the cluster is still expanding in its outer parts and just beginning to fall back in the inner regions ($\lesssim R_{0.3}$) at its very young age of ≈ 1 Myr (Stolte et al. 2004), as can be seen in Fig. 4. In other words, it is practically impossible for NYC to be in dynamical equilibrium at its present age had it undergone a substantial gas-expulsion phase earlier. The computed cluster re-virializes in $\tau_{\rm vir} > 2$ Myr ($< 40\%$ of it; *c.f.* Fig. 4) as opposed to our R136 models (Sec. 3.1) which take ≈ 1 Myr for the same ($> 60\%$ of them; *c.f.* Fig. 1, Table 1).

From proper motion measurements within the central ≈ 1 pc projection of NYC, Rochau et al. (2010) found no notable differences among the 1-dimensional velocity dispersions ($V_{\rm 1d}$) of 4 mass (magnitude) bins over $1.7 - 9 M_\odot$. This indicates that NYC is far from energy equipartition

as it should be if the system is out of dynamical equilibrium (the converse conclusion that non-equipartition implies non-equilibrium, as used by Rochau et al. 2010, is however *not* necessarily true). This is explicitly demonstrated in Fig. 4 (bottom), where the initial separation in $V_{\rm 1d}$ is practically vanished at $t = 1$ Myr due to violent relaxation driven by the gas-expulsion.

The computed $V_{\rm 1d}$ at $t = 1$ Myr is somewhat less than the measured[2] $V_{\rm 1d} \approx 4.5 \pm 0.8$ km s^{-1} and the observed system must currently be super-virial, unlike the computed sub-virial state at $t = 1$ Myr, as the inferred dynamical mass[3] exceeds the photometric mass (Rochau et al. 2010). These can be easily accounted for by a plausible $0.6 < \tau_d < 0.8$ Myr delay in the gas removal (*c.f.* Fig. 4) which would then result in agreement with the observed $V_{\rm 1d}$ and the super-virial state of NYC. Furthermore, NYC's mass is uncertain by a factor ≈ 2 (Rochau et al. 2010).

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[2] The $V_{\rm 1d}$ is obtained from proper motion measurements and is therefore "binary-corrected".

[3] The dynamical $1.7 \times 10^4 M_\odot$, doesn't represent an upper limit as quoted by Rochau et al. (2010), but is only an individual estimate.
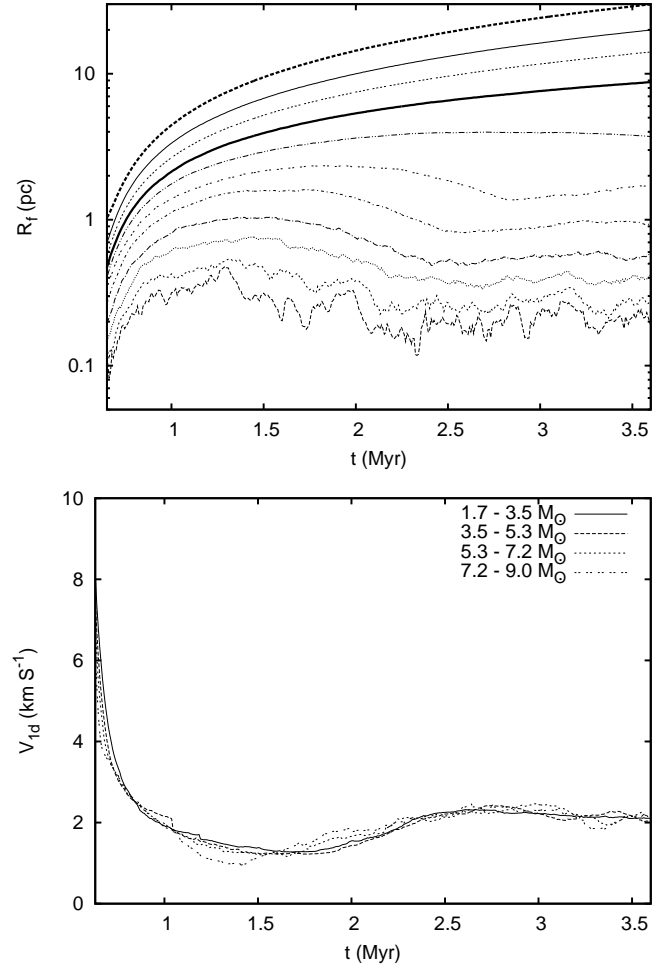
Figure 4. Top: The evolution of the Lagrange radii for the computed NGC 3603 Young Cluster model with $\tau_d = 0$. The legends are the same as in Fig. 1. Bottom: The variation of the 1-dimensional (transverse) velocity dispersion, V_{1d}, within $R < 1$ pc projection, for 4 mass-bins chosen within the same mass range as in Rochau et al. (2010), for the above model. Note that initially V_{1d} differs between the mass bins consistent with energy equipartition. This separation of V_{1d} values vanishes as a result of violent relaxation driven by gas-expulsion. Note that the t-axis of the bottom panel is plotted in the logarithmic scale to highlight this.

Fig. 5 replots Fig. 4 with a $\tau_d \approx 0.6$ Myr delay which, in turn, corresponds to the results of a computation with this delay in gas-expulsion (see Sec. 3.1). This makes the cluster super-virial at its ≈ 1 Myr current age. The corresponding V_{1d} is still somewhat smaller than the observed value but is within 3σ limits. Notably, NYC might, in fact, be somewhat younger (*c.f.* Fig. 4 of Stolte et al. 2004) and V_{1d} also depends on the exact initial mass and size which are subject to uncertainties. Moreover, NYC's V_{1d} and age are susceptible to its distance uncertainties. Notably, Cottaar et al. (2012) also find the Westerlund I cluster sub-virial.

4. CONCLUSIONS AND OUTLOOK

The key message from our above computations and analyses is a reminder that *an observed dynamical equilibrium state of a very young stellar cluster does not necessarily dictate that the cluster has not undergone a gas-expulsion phase.* The non-occurrence of gas-removal

Figure 5. Evolutions of the Lagrange radii (top) and 1-dimensional velocity dispersion (bottom) of the same computed NYC models as in Fig. 4 where an initial gas expulsion time-delay of $\tau_d = 0.6$ Myr is applied while plotting. Hence, the plots are essentially the same as in Fig. 4 except that they begin at $t = 0.6$ Myr and correspond to those from a computation with $\tau_d = 0.6$ Myr (see Sec. 3.1). They show that NYC would be super-virial at its current ≈ 1 Myr age, as observed.

has been highlighted, particularly by putting forward the case of R136, by recent authors, *e.g.*, Hénault-Brunet et al. (2012). This is why we focus on R136 in this study. We also demonstrate, choosing the example of NGC 3606, that lower-mass clusters take much longer to re-virialize (*c.f.* Table 1) so that it is as well appropriate to find non-equilibrium signatures in them. This has been shown to be true also for the ONC by Kroupa et al. (2001) (*c.f.* Table 1). The above must be remembered while interpreting the kinematics of any young cluster.

Notably, R136 exhibits an age-spread; its massive stellar population can be younger, *viz.*, $\lesssim 2$ Myr old (Massey & Hunter 1998). If the gas-expulsion is assumed to commence only after the formation of the most massive stars, a currently equilibrium state is still plausible given the $\tau_{vir} \approx 1$ Myr re-virialization time. It should, however, be remembered that age-estimates of massive stars are highly uncertain. There isn't any concrete evidence that invalidates the scenario involving the formation of R136's entire stellar population at once ≈ 3 Myr (Andersen et al. 2009) ago and the most massive single stars forming

later via dynamically induced binary mergers (Banerjee et al. 2012b) or appearing younger due to mass transfer in close O-star binaries.

Although the present study does not cover a general range of the parameters τ_d, τ_g, $r_h(0)$ and ϵ, these computations can still provide a fair idea of the effects of the variation of these parameters over their plausible ranges. By applying time-shifts to the point of expansion of the clusters in Figs. 1 & 2, it can be concluded that $\tau_d \lesssim 2$ Myr required to find R136 virialized at $t = 3$ Myr, since $\tau_{\rm vir} \approx 1$ Myr. Although an unambiguous τ_d requires radiation hydrodynamic calculations, this upper limit is perhaps too large a value for τ_d in the light of the discussions in Sec. 2.1. The currently chosen values of τ_gs are upper limits based on the typical H II-gas sound-speed of ≈ 10 km s^{-1} (Sec. 2.1). As discussed in Sec. 2.1, the outflow speed can initially be significantly higher than the sound-speed, driven mainly by radiation pressure, resulting in smaller τ_gs than those assumed. This would make the gas-expulsion more prompt, keeping $\tau_{\rm vir}$ practically unchanged.

As for the SFE, the chosen $\epsilon \approx 1/3$ is in the range of the observationally estimated SFEs by Lada & Lada (2003) (see their Table 2). Recent theoretical modelling of star formation with high-resolution resistive magnetohydrodynamics (Machida & Matsumoto 2012) also suggest $\epsilon \approx 33\%$. In any case, a larger ϵ would also result in a bound system and shorter $\tau_{\rm vir}$ as the re-virializing mass would be larger. As for $r_h(0)$s, their increasing values would increase $\tau_{\rm vir}$s, so our conclusions *depend* on our adopted initial high compactness. However, this condition is plausible since such compact star-forming environments (a factor of ≈ 10 smaller than typical young clusters, *i.e.*, $r_h(0) \approx 0.3 - 0.4$ pc) are inferred observationally by André et al. (2011) and as well from the semi-analytic study by Marks & Kroupa (2012) independently (the re-virialization time depends on the above typical compactness but, of course, not on the specific Eqn. (2)). In other words, plausible variations of the model parameters are unlikely to alter our above primary conclusions since none imply a substantial lengthening of τ_d, τ_g or $\tau_{\rm vir}$.

An immediate improvement over the present study would be to introduce an appropriate binary population as in Banerjee et al. (2012a,b). In the light of the present and upcoming observations of Galactic and extragalactic young clusters, an important pending task is to systematically and quantitatively study the effect of gas-expulsion over their entire mass-range with varying parameters such as τ_d, τ_g, $r_h(0)$ and ϵ including realistic stellar populations. Such a model-bank would be extremely valuable to interpret the ever-enriching kinematic data of young stellar clusters.

REFERENCES

Aarseth, S.J., 2003, "Gravitational N-Body Simulations", Cambridge University Press.

Andersen, M., Zinnecker, H., Moneti, A., et al., 2009, ApJ, 707, 1347.

André, P., Men'shchikov, A., Koenyves, V., Arzoumanian, D., Peretto, N. and Palmeirim, P., 2011, in Alfaro Navarro, E.J., Gallego Calvente, A.T., Zapatero Osorio, M.R., eds., "Stellar Clusters & Associations: A RIA Workshop on Gaia", p. 321.

Banerjee, S., Kroupa, P. and Oh, S., 2012a, ApJ, 746, 15.

Banerjee, S., Kroupa, P. and Oh, S., 2012b, MNRAS, 426, 1416.

Baumgardt, H. and Kroupa, P., 2007, MNRAS, 380, 1589.

Baumgardt, H., De Marchi, G. and Kroupa, P., 2008, ApJ, 685, 247.

Brandner, W., 2008, in Beuther, H., et al., eds., "Massive star formation: Observations confront Theory", ASP Conference Series, arXiv:0803.1974 (preprint).

Bressert, E., Bastian, N., Gutermuth, R., et al., 2010, MNRAS, 409, L54.

Bressert, E., Bastian, N., Evans, C.J., et al., 2012, A&A, 542, A49.

Chen, L., de Grijs, R. and Zhao, J.L., 2007, AJ, 134, 1368.

Churchwell, E., 2002, ARA&A, 40, 27.

Cottaar, M., Meyer, M.R., Andersen, M. and Espinoza, P., 2012, A&A, 539, A5.

Crowther, P.A., Schnurr, O., Hirschi, R., et al., 2010, MNRAS, 408, 731.

Elmegreen, B.G., 1983, MNRAS, 203, 1011.

Elmegreen B. G., Efremov Yu.N., Pudritz R. E. and Zinnecker H., 2000, in Mannings V. G., Boss A. P., Russell S. S., eds, "Protostars and Planets IV", NATO Science Series C, Vol. 540. Univ. Arizona Press, Tucson, p. 179.

Evans, C.J., Taylor, W.D., Hénault-Brunet, V., et al., 2011, A&A, 530, 108.

Geyer, M.P. and Burkert, A., 2001, MNRAS, 323, 988.

Goodwin, S.P., 2009, Ap&SS, 324, 259.

Gutermuth R.A., Pipher J.L., Megeath S.T., Myers P.C., Allen L.E. and Allen T.S., 2011, ApJ, 739, 84.

Hénault-Brunet, V., Evans, C.J., Sana, H., et al., 2012, A&A, 546, A73.

Hennemann, M., Motte, F., Schneider, N., et al., 2012, A&A, 543, L3.

Hill, T., Motte, F., Didelon, P., et al., 2011, A&A, 533, A94.

Hills, J.G., 1980, ApJ, 235, 986.

Hurley, J.R., Pols, O.R. and Tout, C.A., 2000, MNRAS, 315, 543.

Hurley, J.R., Tout, C.A. and Pols, O.R., 2002, MNRAS, 329, 897.

Jones, B.F. and Walker, M.F., 1988, AJ, 95, 1755.

Kroupa, P., 2001, MNRAS, 332, 231.

Kroupa, P., Aarseth, S. and Hurley, J., 2001, MNRAS, 321, 699.

Kroupa, P., 2008, in Aarseth, S.J., Tout, C.A., Mardling, R.A., eds, Lecture Notes in Physics Vol. 760, Initial Conditions for Star Clusters. Springer-Verlag, Berlin, p. 181.

Kroupa, P., Weidner, C., Pflamm-Altenburg, J., et al., 2013, to appear in Gilmore, G., ed, "Planets, Stars & Stellar Systems", Stellar Systems and Galactic Structure, Vol. V, arXiv:1112.3340 (preprint).

Krumholz, M.R. and Matzner C.D., 2009, ApJ, 703, 1352.

Küpper, A.H.W., Maschberger, T., Baumgardt, H. and Kroupa, P., 2011, MNRAS, 417, 2300.

Lada, C.J., Margulis, M. and Dearborn, D., 1984, ApJ, 285, 141.

Lada, C.J. and Lada, E.A., 2003, ARA&A, 41, 57.

Lada, E.A., 1999, in Lada C. J., Kylafis N. D., eds, "The Origin of Stars and Planetary Systems", NATO Science Series C, Vol. 540. Kluwer, Dordrecht, p. 441.

Littlefair, S.P., Naylor, T., Jeffries, R.D., Devey, C.R. and Vine, S., 2003, MNRAS, 345, 1205.

Liu, T., Wu, Y., Wu, J., et al., 2012, arXiv:1211.5206 (preprint).

Machida, M.N. and Matsumoto, T., 2012, MNRAS, 421, 588.

Malinen, J., Juvela, M., Rawlings, M.G., Ward-Thompson, D., Palmeirim, P. and André, Ph., 2012, A&A, 544, A50.

Marks, M. and Kroupa, P., 2012, A&A, 543, A8.

Massey, P. and Hunter, D.A., 1998, ApJ, 493, 180.

Mathieu, R.D., 1983, ApJ, 267, L97.

Patel, N.A., Curiel, S., Sridharan, T.K., et al., 2005, Nature, 437, 109.

Peters, T., Klessen, R.S., Mac Low, M.-M., and Banerjee, R., 2010, ApJ, 725, 134.

Peters, T., Klessen, R.S., Mac Low, M.-M., and Banerjee, R., 2011, in Alfaro Navarro, E.J., Gallego Calvente, A.T., Zapatero Osorio, M.R., eds, "Stellar Clusters & Associations: A RIA Workshop on Gaia", p. 229.

Pfalzner, S., Kaczmarek, T. and Olczak, C., 2012, A&A, 545, A122.

Portegies Zwart, S.F., McMillan, S.L.W. and Gieles, M., 2010, ARA&A, 48, 431.

Rochau, B., Brandner, W., Stolte, A., et al., 2010, ApJ, 716, L90.

Sana, H. and Evans, C.J., 2011, IAUS, 272, 474.

Sana, H., de Koter, A., de Mink, S.E., et al., 2012, A&A accepted, arXiv:1209.4638 (preprint).

Schneider, N., Csengeri, T., Bontemps, S., et al., 2010, A&A, 520, A49.

Schneider, N., Csengeri, T., Hennemann, M., et al., 2012, A&A, 540, L11.

Stolte, A., Brandner, W., Brandl, B., et al., 2004, AJ, 128, 765.

Stolte, A., Brandner, W., Brandl, B., et al., 2006, AJ, 132, 253.

Weidner, C. and Kroupa, P., 2004, MNRAS, 348, 187.

Wünsch, R., et al., 2011, ApJ, 740, 75.

Zinnecker, H., McCaughrean, M.J. and Wilking, B.A., 1993, in Levy E.H., Lunine J.I., eds, "Protostars and Planets III", NATO Science Series C, Vol. 540. Univ. Arizona Press, Tucson, p. 429.